THE ION FUNCTIONS OF ONE-DIMENSIONAL ACTIVE PLASMA LAYER OF HIGH-CURRENT GAS DISCHARGES

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Active plasma layer (APL) is a quasineutral plasma area bordering with cathode space charge layer. All generated in APL ions get to cathode. In [1] it has been shown, that in intensive discharges there is a multiple gas compression in APL. In the present work the important characteristic of discharges, P_0, equal to number of ions coming on cathode in recalculation on one neutral flying from cathode is considered. The dependence of this value on parameters of discharge is named an ion function. The low-voltage case, when energy of cathode electrons does not exceed several neutral ionization energies, and the high-voltage case, when density of primary electrons current in APL is supposed to be a constant, but their average energy changes only, are discussed.

1. One-dimensional APL

Let there be emitted an electron current with density $j_{e0} = j_e(0)$ and a neutral flow with density $q_0 = q(0)$ and average directional velocity $v_0 = 0.5\sqrt{8T_0/\pi M}$, along an axis x, which is normal to a flat homogeneous surface of cathode, where T_0 - temperature of cathode in energy unities, M - neutral mass. Ions with current density $j_i(x) \geq 0$ and neutral flow with density $q_{back}(x) \geq 0$ move to cathode. Neutral backflow is caused partly by resonant charge exchanged ions ($q_{ch}(x)$), partly by presence of gas on anode boundary of APL ($q_{ex}(x)$).

Obviously, in stationary APL the conservation of heavy particles flow takes place

$$Q(x) - Q_{back}(x) - P(x) = D = const, \qquad (1)$$

where neutral flows are normalized to quantity q_0; $P(x) = j_i(x)/eq_0$; e - the elementary charge. If $D = 0$, we deal with an non-consumed operating mode of cathode. When $D < 0$ cathode immerses gas, if $D > 0$ material of cathode is constantly spent.

Let's write down a simplified system of the continuity equations for neutrals and ions, and the equation for energy flow of primary electrons in APL

$$dN/ds = -\alpha(V)KN - \beta PN, \qquad (2)$$

$$\omega^{-1}dN_{ex}/ds = -\alpha(V)KN_{ex} - \beta PN_{ex}, \qquad (3)$$

$$dP/ds = -\alpha(V)K(N + N_{back}), \qquad (4)$$

$$d(KV)/ds = W(V)dP/ds, \qquad (5)$$

where $\omega = v_0/v_g = \sqrt{T_0/T_g}$; $v_g = 0.5\sqrt{8T_g/\pi M}$ - average velocity of directed to the cathode neutral flow in the region of anode boundary of APL; neutral densities are normalized to quantity n_0 ($q_0 = n_0 v_0$); $s = n_0\sigma_m x$; σ_m - the peak value of electron-neutral ionization cross-section; $\lambda = v^2/4\delta^2$; $\varepsilon(s)$ - average primary, accelerated in cathode space charge layer, electron energy; φ_i - neutral ionization potential; $\alpha(V) = \sigma_i(V)/\sigma_m$; $\beta = \sigma_n/\sigma_m$; $\sigma_i(V)$ and σ_n - ionization and resonant charge exchange cross-sections, respectively; $K = j_e(s)/eq_0$; $W(V) = w(V)/e\varphi_i$; $w(V)$ - average energy a primary electron spends for one act of ionization. Thus we consider, that all ion current acting on cathode is generated due to ionization by primary electrons in APL, and neutral "burning" occurs due to ionization by primary electrons and resonant charge exchange processes. Slow electrons ionization and recombination processes in APL are neglected.

From (2) and (3) we shall receive $N_{ex} = \omega(\Pi - D)(\Pi/N)^{\omega}$, where $\Pi = Q(s_a)$ - normal transparency of APL ($\Pi \geq 0$; $\Pi \geq D$); s_a - APL thickness, so taking (1) into account we shall have

$$N + N_{back} = kN + (\omega + 1 - k)(\Pi - D)(\Pi/N)^{\omega} - (k-1)(P + D), \qquad (6)$$

where $k = 1 + v_0/u$; u - average velocity of charge exchanged neutrals ($u > v_0 \geq v_g$).

In the ionization mode (when $i_0 << i_{0m}$, where $i_0 = j_{i0}/j_{e0}$, and i_{0m} - the peak value of i_0, achievable at the complete cathode electrons relaxation in APL) the flow of charge exchanged neutrals in APL is small, therefore, by setting in (1) $Q_{ch} = 0$, we find $P(N) = N - (\Pi - D)(\Pi/N)^{\omega} - D$, and since $P(1) = P_0$, then

$$P_0 = 1 - \Pi^{\omega+1} - D(1 - \Pi^{\omega}). \qquad (7)$$

2. Low-voltage APL

In this case, when $V_0 \leq 3 \div 4$, it is possible to account, that $V(s) = V_0 = const$ and $W(V) = W(V_0) = W_0 = const$, so using (5) we find

$$K = i_{0m}^{-1}[P + P_0(i_{0m}/i_0 - 1)], \qquad (8)$$

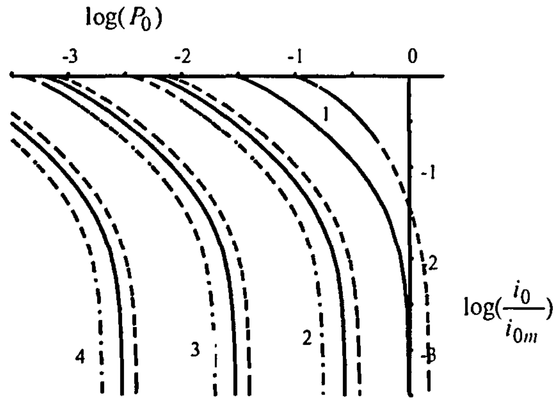

Fig.1. The ion functions of low-voltage APL, received by the numerical solution (11) at $i_{0m}\chi = 50$, $k = 3/2$ and $\omega = 2$. Solid lines are plotted at $D = 0$, dotted - at $D = -0.5$, and dash-dotted - at $D = 0.5$. Groups of curves 1, 2, 3 and 4 correspond to transparences $\Pi = 10^{-6}$, $\Pi = 0.9$, $\Pi = 0.99$ and $\Pi = 0.999$, respectively.

$$i_{0m} = V_0 / W_0. \qquad (9)$$

It is known, that at the large energies of electrons ($V >> 1$) $W(V) \cong 2$ for every gas. At the small energies we shall account, that $W \to \infty$ at $V \to 1$. Therefore the dependence $W(V)$ can be approximated by the expression $W(V) = 2V/(V-1)$. For dependence $\alpha(V)$ we put $\alpha(V) = (V-1)/V$. Then using (9) we find

$$i_{0m} = (V_0 - 1)/2. \qquad (10)$$

From (2) and (4) taking (8) into account we receive

$$N[(1 + i_{0m}\chi)P + A]dP/dN = (P + A)(N + N_{back}), \quad (11)$$

where $\chi = \beta/\alpha(V_0)$, and $(N + N_{back})$ is defined by (6); $i_{0m}\chi = \beta V_0/2 >> 1$, $A = P_0(i_{0m}/i_0 - 1)$.

3. High-voltage APL

Let's consider, that in this case initial energy of electrons is much greater than the energy loss for one act of ionization $V_0 >> W(V_0)$, that is approximately $V_0 \geq 10$. We shall restrict voltages from above to the requirement of applicability of approximation $\alpha(V) = (V-1)/V$ to within the coefficient $\cong 2$. Then $V_0 \leq 50$.

Obviously, in the high-voltage case it is practically always possible to account, that primary electrons do not transfer in slow group, and spend on ionization only the energy, that is $K(s) \cong K_0 = const$. In this case from (5) we shall receive $i_0 = (V_0 - V_a)/2 - \ln(V_0/V_a)/2$, where $V_a = \varepsilon(s_a)/e\varphi_i$; $\varepsilon(s_a)$ - average energy of an electron beam leaving APL. Setting $V_a = 1$, we shall have

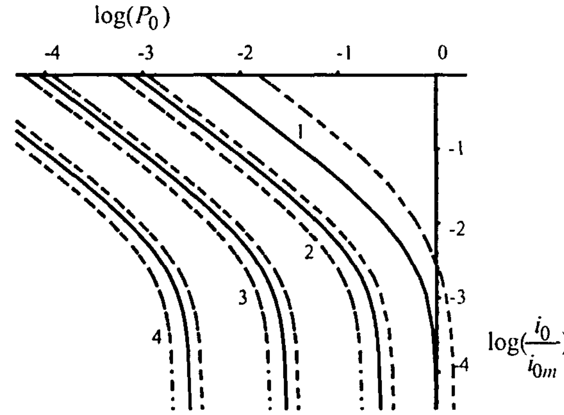

Fig.2. The ion functions of high- voltage APL, received by the numerical solution (13) at $V_0 = 30$, $\beta = 50$, $k = 3/2$ and $\omega = 2$. Solid lines are plotted at $D = 0$, dotted - at $D = -0.5$, and dash-dotted - at $D = 0.5$. Groups of curves 1, 2, 3 and 4 correspond to transparences $\Pi = 10^{-6}$, $\Pi = 0.9$, $\Pi = 0.99$ and $\Pi = 0.999$, respectively.

$$i_{0m} = (V_0 - 1)/2 - \ln(V_0)/2 \approx V_0/2. \qquad (12)$$

The basic equation determining the high-voltage APL ion function, we shall receive from (2), (4), (5) and (12)

$$N[\alpha(V)P_0 + i_0\beta P(V)]dV/dN = 2i_0(N + N_{back}), \quad (13)$$

where

$$P(V) = P_0[V - V_a - \ln(V/V_a)]/2i_0, \qquad (14)$$

and $(N + N_{back})$ is defined by (6).

4. Conclusion

In high-current discharges there is strong "burning" of gas in APL ($\Pi << 1$). Thus in ionization mode ($i_0 << i_{0m}$) gas is kept near to cathode due to ionization ($P_0 \approx 1$). In charge exchange mode ($i_0 = i_{0m}$) gas is kept due to resonant charge exchange processes ($P_0 << 1$), and in the high-voltage case charge exchange efficiency grows due to increase in APL thickness.

5. Acknowledgements

The author would like to thank Prof. A.V.Zharinov for the fruitful discussions.

This work has been partially supported by RFBR Grant No 01-02-16014.

6. References

[1] Zharinov A.V. *Proc. of XXV ICPIG*. Ed. by Toshio Goto. Japan: Nagoya University, 3 (2001) 335.